

LEAN MANUFACTURING PRINCIPLES AND THEIR APPLICABILITY TO THE MINING INDUSTRY

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Lean manufacturing, pioneered by Toyota, has been credited with the most significant improvements in production efficiency and product quality since the transformation from craft manufacturing to mass production in the early 20th century. It represents a comprehensive philosophy for structuring, operation, control, and management of production systems that is believed to have wide applicability. This paper outlines major lean manufacturing principles and discusses their potential for application in the mining industry.

1. Introduction

In the 1970s, the high performance of Japanese manufacturing, in terms of cost, quality, delivery, and flexibility became apparent throughout the world. Initially, this success was credited to diverse reasons such as Japanese culture and the work ethic it espouses, the use of just-in-time production control, and the widespread adoption of the total quality principles of Deming and Juran. Indeed, these were all factors contributing to the success of the Japanese. However, it was not until the early part of this decade that many Americans came to understand that these elements were merely pieces of a comprehensive philosophy of production system design, operation, and management. The highly popular books by Womack and Jones^{1,2} clearly outlined this philosophy. Moreover, they demonstrated that, in the automotive industry, lean manufacturing offered more than a 2.5:1 cost advantage over the mass production approaches traditionally practiced. Only the earlier transition from craft manufacturing to mass production lead by Henry Ford and others in the early 20th century has offered more dramatic cost advantages (estimated at a 9:1 ratio).

Such a cost advantage, of course, is so significant that once a few companies in a particular industry adopt lean practices, laggards will eventually be forced out of business. As a consequence, most major automobile manufacturers have initiated a transition to lean manufacturing and some now have quite mature systems in place. Lean transitions at a number of non-automotive U.S. manufacturers have been documented, illustrating the truly dramatic performance gains.^{2,3} In U.S. manufacturing today there is widespread acceptance of lean principles and intense activity to implement them (far from a simple undertaking). Moreover, many believe that the lean approach has general applicability to nearly any type of production system. Applications at operations as diverse as low-volume (e.g. aircraft) manufacturing, office processes, construction, and oil well drilling are now being implemented. Given the success of this production strategy, it is appropriate to consider its possible application to the mining industry. This paper is intended to introduce the lean philosophy to mine operators and discuss the potential for application within our industry.

We begin the paper by outlining the objectives of lean production. Subsequently, we provide an overview of the lean philosophy. Here, we outline the major elements and principles of this philosophy. We also selectively present particular practices in lean production, focusing, for the most part, on those with potential role in mining. We illustrate these principles with potential applications in the mining industry. These illustrations include situations where the principles have already been applied, common practices that are counter to the lean philosophy, and new applications where lean concepts would appear to be feasible and offer benefits. Note that this type of illustration is piecemeal in nature. In practice, however, it is important that lean be implemented as a total system for production process design and management.

2. Objectives of Lean Production

Lean production systems have three major objectives:

- Highest customer satisfaction — this objective has two aspects. The first is to provide customers products with the combinations of quality, functionality, and price that lead to their greatest satisfaction. The second involves meeting stringent delivery requirements, consistently providing the quantity of product demanded in a timely manner. In depth knowledge of customer needs and values is actively sought in lean production and both the product itself and the production process are carefully designed to respond to these needs and values.
- Total elimination of waste — each step in the production process is critically examined to insure that it adds value from the customer's perspective. Any non-value-added operation is considered waste, or *muda*, and action is taken to eliminate that waste. General examples of waste include inventory, set-up costs, product defects, inefficient operations, and transportation. When lean is initially introduced, waste elimination efforts sometimes include radical restructuring of

the production system (process razing). Subsequently, day-to-day incremental gains are also actively sought through adoption of continuous improvement (kaizen) practices.

- Highest respect of human dignity in the production process — the name “lean” is a somewhat unfortunate choice because, to the uninformed, it sometimes connotes minimising the labor force through downsizing and layoffs. From the lean perspective that is “mean” manufacturing, totally contrary to the lean philosophy. Lean manufacturers sincerely view their employees as their most important assets. They actively seek to establish a safe, secure, and fulfilling work environment where workers can flourish. Lean workers are valued for their minds more than their hands. For both their personal fulfillment and the benefit of their employer, they are expected to make intellectual contributions on process improvements. The benefits realised from these improvements are recognised to outweigh by far, the costs of establishing such a work environment. Note that these costs are significant and include both high wages and high job security. Lean production aggressively and systematically seeks and implements these intellectual contributions from every individual, at every level, in the organisation. In so doing, it becomes a *learning organisation* with its capabilities and level of performance constantly evolving to higher and higher levels over time. Like mean manufacturers, lean manufacturers do seek to make their products with minimal labor. However, only at lean manufacturers are the shop floor employees the ones who make it happen.

3. Basic Concepts and Structure of Lean Manufacturing

Lean manufacturing is based on four major concepts as illustrated in Fig. 1. We now consider each of these concepts in turn, defining their meaning, interrelationships, and supporting practices. We explain how, collectively, they comprise a paradigm for design, operation, and management of production processes, one that has proven to be highly effective in practice.

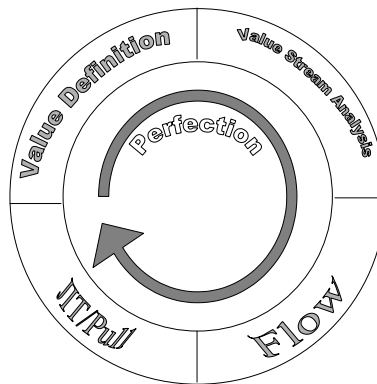


Fig. 1. Structure of lean production.

4. Value Definition and Value Stream Analysis

Value definition focuses on understanding customer needs and desires for product functionality, quality, and delivery as well as the relationship of these three items to market price. This requires extensive market research, which may include the use of tools such as quality function deployment (QFD). QFD is a methodology to identify and prioritise customer needs and to translate these characteristics to specific design characteristics.^{4,5} For example, a customer's desire that a car be easy to park might be translated to specifications involving its turning radius, length, and side and rear visibility. Alternatively, a utility's desire that a coal be "easy to handle" might be translated to particular product specifications involving acceptable combinations of moisture content, size distribution, and ash composition. This information is subsequently utilised in the QFD methodology to prioritise product design issues and define target values for the product specifications that are achievable and will result in improved customer satisfaction and competitiveness of the product in the marketplace. It is also used to insure that the production process is appropriately designed and operated to serve customer needs. We note that value definition considers needs of intermediate as well as ultimate customers, e.g. rail haulers might be an intermediate customer for steam coal and their needs would be considered in addition to those of the utility.

The design of the product focuses on value, defined as the ratio of the perceived benefit of a product attribute divided by the cost of that attribute. Note that techniques are available to quantify this measure. Through *value engineering*, lean manufacturers identify and focus on both high and low value product attributes. High value attributes represent opportunities where low cost enhancements of product specifications can result in large gains in perceived customer value and realised price in the marketplace. Low value attributes are ones where there is a strong need for innovation or major change in product design.

Lean manufacturers manage their product offerings to the marketplace through an approach called *target costing*.^{6,7} Under target costing, the company defines a product mix that meets the needs of targeted market sectors and defines the market price that would be realised for each product in that mix. Subsequently, profit objectives from the company's business plan are used to establish stringent, but achievable, goals on the cost of production of each product. Product design and specifications are adjusted and production processes are improved in order to attain target cost objectives. This approach recognises that the marketplace, not the producer, sets the product selling price and improved profitability can only be attained through cost reduction. It insures that the product mix is appropriate to meet profitability objectives and maintains the company on a track of continuous reduction of the cost of production.

Note that relationships between market makers (the company that produces the final product) and their suppliers differ in lean relative to traditional production systems. The market-maker in traditional systems defines product specifications that

they desire and seeks competitive bids to obtain that product from the marketplace at minimum cost (reliability and quality of the supplier is, of course, considered in all contract award decisions). Suppliers often bid low to obtain the business and hope to raise prices over time. Relationships between the supplier and market maker are at arm's length and generally short term in nature. In lean production, suppliers themselves are brought in early to the product design process. In setting product specifications, care is taken to insure that they do not pose unforeseen burdens on the supplier and incorporate opportunities for cost savings identified by the supplier. The objective is to consider the entire value stream, not just the parochial needs of the market maker. Relationships between the market maker and supplier are much more cooperative, there is much greater information sharing, the supplier might actually design their part of the final product, and formal business partnerships are often established. Innovation is the most valued supplier attribute. Market-makers do maintain an adequate supplier base to avoid risk of disruption; but they reward the innovative suppliers within this base with a larger share of business, maintain volume with these suppliers in market downturns, and are proactive to insure the profitability of these suppliers. Suppliers agree to target costs for their portion of the final product. They are expected to have their own culture of continuous improvement and consequently are expected to provide their product at reduced cost to the market-maker over time, a fact reflected in target costs. For incentive, of course, the supplier retains a substantial fraction of any cost savings they develop. Finally, we note that lean production is greatly facilitated when lean practices are followed by the market maker, its suppliers, their suppliers, etc. throughout the extended enterprise.

The value definition just discussed provides the foundation for *value stream analysis*. This analysis begins with *process mapping*, defining each step followed in the process to make the product. Of each step the question is asked "does it add value to the product from the customer's perspective?". Specifically, this requires that the step involve enhancement of the product's functionality and or quality. This generally involves a material change of the product, although not all material changes add value. We subsequently seek to eliminate non-value-added steps in the process as well as to enhance the efficiency of value-added steps.

It is critical to thoroughly understand customer needs in this analysis. For example, an egg producer places its eggs in protective cardboard cartons before shipping them to the bakery where they are consumed for commercial bread making. After value stream analysis, it is realised that the expensive cartons really just protect the eggshells, not the eggs (i.e. the yokes and whites). The eggshells, of course, have no value to the bakery. It makes sense to remove the shells at the egg producer and send only the yokes and whites to the bakery. This can be done using recyclable containers at much lower total packaging and transportation costs. It is critical that efforts in process mapping and value stream analysis cross inter-organisational boundaries since the greatest wastes often occur at those boundaries. Such waste occurs so frequently in practice because each organisation on the value

stream views matters parochially and does not, as in the example above, align its operations to the values of the ultimate customer.

It is recognised that most production operations are, in fact, wastes; and seven general categories of wastes have been identified. These include the wastes of overproduction, inventory, making defects, inefficient operations (especially wasted human motion and low equipment reliability), transportation (*all* transportation is waste), inspection, and untapped human creativity in improving operations. Overproduction results in reduced profitability because production is not precisely matched to demand resulting in losses through obsolescence, spoilage, and discounting to sell excess inventories. (We believe that discounting losses that occur as a consequence of overproduction are particularly significant in parts of the minerals industry.) Inventory itself (both in-process and finished goods) is generally regarded as the worst of these wastes because it hides, or obscures the causes, of other wastes in the production process. For example, a large stockpile of finished stone might exist to serve customers because of a lack of reliability in the production process that would otherwise make the stone to order.

Process steps that are wastes are classified into one of two categories: those required by current production operations and those not required. Those in the latter category are eliminated immediately. However, it is an important objective to identify those in the later category so that long-term efforts can focus on eliminating them.

We also note that process mapping and value stream analysis can occur at a number of levels. These levels range from the macro that looks at the entire value stream in broad steps across inter-organisational boundaries to the micro where an individual operation is analysed in fine terms, such as analysis of individual hand and eye motions. In general, greater benefits result from higher level analysis, but low level focus is also valuable, especially for high-volume, repetitive production processes. This type of detailed analysis should strongly involve the shop floor workers themselves. (Note that in the lean organisation, all lower level supervisors or team leaders and to some degree every worker is trained in fundamental industrial engineering principles such as motion analysis, time study, ergonomics, and basic capacity analysis principles. Everyone in the company is an industrial engineer.)

4.1. *Potential mining applications*

As an example of high-level value definition and value stream analysis, we consider what could be and is, to some degree, happening in the steam coal industry in the United States. Here, electricity is the product and the businesses and residences that consume it are the ultimate customers. Utilities would be the market maker and coal producers would be their critical suppliers. There are undoubtedly numerous opportunities to better align the value stream with customer needs, especially at boundaries between the utilities and the coal producers. Indeed, in the U.S.,

utility deregulation is helping to eliminate artificial barriers to such realignment. In strategic planning, lean power generators would assess their ability to deliver low cost power in various sectors of the country and that ability relative to their competition. This would consider total system costs from transmission back to coal extraction. The waste of fuel transportation, a highcost, non-value-added activity, would strongly influence this analysis and would be reflected in coal supplier selection, generation level assignments to existing plants, location of new plants (e.g. mine mouth or river-side), etc.

For a lean utility, relationships, perhaps business partnerships, might be forged with reliable, innovative, strategically located lean coal suppliers. In a target costing process lead by the utilities, coal suppliers would be intimately involved in fuel design and specification. For example, the ash specification would consider combustibles losses during preparation as they vary with cleaning at different separation gravities, the cost of transporting the ash from the mine to the utility, and the cost of handling/pulverising a higher quantity of fuel for a given energy yield at the boiler, derating losses as a function of ash levels (energy input to the boiler might be constrained when feeding high ash coal when pulverisers are down) and disposing the ash in an environmentally safe manner as bottom or flyash at the utility. The ash would be specified at a level that optimizes these tradeoffs, thereby considering total system costs, not be limited by the parochial perspective of the utility. Similar analysis would be made for other specifications.

Similarly, a lean coal producer with a diverse resource base (e.g. a multi-seam property) would carefully define the product mix that it delivers to market. In making this definition, the operator would consider market price as a function of quality and optimized extraction sequencing, preparation, and blending of the resource base in order to deliver maximum value. (Carelessness in this regard can lead to tremendous opportunity losses when low quality portions of the reserve must be sold in low quality/low price products.) Target costing might be utilised to discipline the production system and insure profitability.

In this regard, note that margin-based pricing is generally considered inappropriate under the lean philosophy. In mining, this would involve increasing production volume at a mine, and selling the product at a price that exceeds the marginal cost of production. This cost (and often the selling price) might, at times, be low since production might be obtained consuming low-cost slack capacity (e.g. the prep plant could produce 220 tons per day more on its current operating schedule at the small incremental costs of reagents, power, and equipment wear) and fixed costs (e.g. for the belt crew) are not assigned to the marginal units of the product. Margin-based prices have only short-term relevance dependent on current capacity utilisation. The lean perspective is that strictly market-determined prices should be used in production decisions that consider a long time horizon. Only products that enable the company to meet its planned profitability should be produced and sold. It recognises that capacity is under management control and should be adjusted in accordance with the long-term plan (see the discussion of “flexibility” below).

In mining there is an additional reason to be careful with margin-based pricing. Mineral reserves are exhaustible. There may be an opportunity cost since a unit sold today on marginal cost cannot be sold later at market price. Margin-based pricing decisions tend to be near-sighted.

Note that these examples have addressed the value-stream from a high-level, global perspective. In lean production, this stream is simultaneously assessed and improved locally from a detailed, but not near-sighted, perspective. The work of improving the value stream is the responsibility of the entire human resource base of the firm. The strategy is to scrutinize each operation and work to insure that it adds value from the perspective of the ultimate customer and, if it does not, to eliminate or minimise the amount of waste.

5. Flow

The concept of flow may be expressed in terms of two ideals that the lean producer strives to implement in the structure and operation of a production system:

- *Continuous flow* — products should flow continuously through (exclusively) value-added operations without delay, and
- *Leveled production* — produce every product in the product mix every day in direct proportion to demand for that product (the word “day” is intended only as a proxy for an appropriate short interval of time, the shorter the better).

There is both a direct and an indirect motivation for these two ideals. The direct motivation is that they enable the production system to respond directly to market demand. “Continuous flow without delay” implies minimum production lead-time. When lead times are less than the customer’s acceptable waiting time until delivery, companies can schedule production make-to-order instead of a make-to-stock. Moreover, the leveling ideal implies close coordination between what is produced and what the customer demands over time. Together these two ideals enable a company to avoid the wastes of overproduction noted above.

The indirect, but even more important, motivation for these ideals is that the focus on flow motivates perfection of operations along several other major dimensions of performance, as we will now explain. Since product residence time in inventory is the basic source of all delay, the ideal “continuous flow without delay” implies zero in-process inventories, eliminating the associated wastes of inventory mentioned above. Low inventory systems, in turn, are extremely susceptible to even minor process disruptions so that highly *stable* operations must exist as a precondition for flow. Furthermore, the leveling ideal can only be achieved through *flexible* operations that can easily switch from making one product to another. We now elaborate further on the means used to achieve stability and flexibility in the lean production systems.

5.1. Flow prerequisites

5.1.1. Stability

A stable process is one that produces products with 100% quality, is available continuously throughout the entire scheduled production interval, and consistently completes its task within a defined operating time. A high degree of stability is a prerequisite to flow because it minimises operational disruptions, which are difficult to tolerate in continuous flow systems. These disruptions are consequences of machine breakdowns, product defects, and variable operating times, factors that have been minimised in stable processes. In lean production systems, stability is achieved through practices such as standardised work, quality at the source, and total productive maintenance.

5.1.2. Standardised work

The term “standardised work” has been around in manufacturing since the days of Taylor, but the lean definition differs from the traditional one. In lean production, standardised work begins with a statement of best practice for completing a job. It expresses the current state of learning about the process and prescribes the procedure for performing the operation with minimum human effort, maximum safety, zero defects, minimum time/manpower, and minimum ancillary waste such as scrap and energy losses. It forms a basis for training, and all workers are expected to follow the prescribed procedures conscientiously. It is a common practice to post a description of standard procedures at the workstation with special effort taken to communicate key motions and process checks. In lean production, standardised work procedures do not come down from management. Instead, they are established and to some degree “owned” by the workers themselves. They are intended to be a product of the *collective brainpower* of all team members that work the operation in question. The workers are both encouraged and provided the necessary background training to analyse and constantly improve standard procedures. Useful suggestions are formally sought, rewarded, and implemented immediately; and the standard procedures are updated as learning evolves to a higher level. Importantly, standardised work reduces variability of processing times relative to what exists in their absence. This eliminates the numerous negative effects that variability inevitably has on the performance of continuous flow systems (e.g. capacity reduction, and buffer stock requirements).

Potential for Mining Application: In light of using standardised procedures, one often hears the claim a “mine is not a factory” referring to the numerous factors presumably beyond control of management. We believe that control of the production environment is certainly more difficult in mining and most standardised procedures would have to have higher flexibility than standardised work statements in a factory. However, this difficulty is not an excuse for the absence of such procedures. Without them, work can rapidly degrade to seat-of-the-pants with little or

no potential for learning and improvement. Transfer of skills between machine operators is much more difficult than it need to be. Moreover, their absence is equivalent to washing one's hands of the responsibility to control the work environment when that control is, with effort, care, information, and creativity, possible.

One of the authors knew of a continuous miner operator who had a deserved reputation of being the best operator at any of the mines where he worked. When asked by management to explain how he did it, he simply lied. He viewed his discoveries as his own "secrets" and his personal guarantee of job security. In a lean system, he would be comfortable in his security with the company; and he would be rewarded, both financially and with esteem, for sharing these "secrets." All of the other miner operators at this company would then benefit from his insights and discoveries.

5.1.3. *Quality-at-the-source*

Quality-at-the-source⁸ is the recognition that quality should be built into the product throughout all steps of the production process. It should not be inspected and/or reworked, into the product. In traditional production systems quality control is typically attained by random sampling of the product stream at designated checkpoints that are often remote in time and space from the production operation that caused the defect. Control actions are taken in response to feedback information from the discovered defects. However, because of this remoteness, the information is not particularly diagnostic. Moreover, because only a fraction of the products are inspected, defects can escape the system. In contrast, in lean production, one strives for 100% inspection for quality at each operation and each immediately downstream operation in order to localise and identify the source of defects immediately (*self and successor inspection*). Inspection is part of the standardised work description at the workstations and performed by the workers themselves; separate "inspectors" are not employed. Moreover, in contrast to traditional inspection systems, lean production strives to make quality control feedforward by taking proactive measures to identify and correct errors before defects occur. One strategy for doing this is through condition (or machine state) monitoring. Sensors detect when environmental conditions deviate from target ranges and warn the operator to correct the situation before continuing. Another strategy is the development of mistake-proofing (poke-yoke) systems. These are mechanical, electrical, or work design systems that preclude or reduce the incidence of human errors in executing an operation. They are generally inexpensive, and shop floor workers themselves assist in the development of poke-yoke devices.

Potential for Mining Application: We note that there is generally less quality awareness among workers in mining than in manufacturing and process industries. With respect to the product itself, the reason for this is understandable. Quality is largely a function of ore selection, it is impacted by many uncontrollable factors, and quality control is largely left to the beneficiation plant. However, this overlooks

significant operator impacts on product quality. Cutting and loading procedures that minimise ore dilution would be valuable at any operation. Indeed, one of the authors is aware of a mine where great care taken to prevent out-of-seam dilution has enabled the mine to avoid washing a large fraction of the coal stream (with the assistance of an on-line analyser to segregate the low ash material on the conveyor belt). A lean mine would discover and incorporate these procedures in its statement of standardised work.

To illustrate a poke-yoke device in mining that would be a direct transplant of a common factory strategy called the *counting method*, consider a coal loading and blending operation using front-end loaders. Two scoops are to be taken from pile A for every one from pile B in order to obtain the desired blending ratio. Pressure sensors located on the ground in front of each stockpile could be connected to a microprocessor that monitors the loading sequence and triggers a visual or audio alarm when a loader approaches the wrong pile.

Quality-at-the-source applies, of course, to both ancillary work and to safety as much as it does to product quality. These principles could be implemented to insure that a roof bolt is installed properly, a face is only cut under safe conditions, a blast hole is loaded correctly, or a stopping is built properly. The key ideas are (i) to define common human errors and establish mechanisms to proactively prevent these mistakes and/or (ii) to define environment measures that insure quality and safety and to monitor these variables, providing alarms or shutdowns when they deviate from specifications.

5.1.4. Total productive maintenance (TPM)

TPM⁹ is an extension of the American concept of preventive maintenance (PM). In preventive maintenance, maintenance activities are scheduled to service the machine and replace worn components in order to minimise the incidence of machine breakdowns during scheduled production time. TPM extends the concept of PM to better insure that the machine is in a perfect working state when it is scheduled to be available for production.

A major theme of TPM is a much higher involvement of the machine operator in equipment maintenance. Concerning the roles of the machine operator and the maintenance technician, a mother/doctor analogy is often used. (We apologise that the analogy has a somewhat dated perspective on gender roles in a marriage. Feel free to substitute “father” for “mother” in the description below.) The machine operator is the mother of her machine. As mother, she first emphasises “healthy living” through proper operation of the equipment. It must not be operated in abnormal modes or circumstances that might cause damage. State monitoring of the equipment is employed and it must not be operated when the monitors indicate problems. The mother is empowered (and expected) to shut the machine down at any sign of a health problem. Moreover, the mother herself performs routine PM following standard work procedures strictly and on schedule. (She will have

taken extensive training on how to do this.) The mother also treats minor illnesses of the machine (i.e. makes minor repairs). The maintenance technician is the doctor and his/her role is in treating more serious illnesses as well as rigorous inspections that it is impractical for the mother to perform. The mother, however, should be present and assist during these inspections and repairs and might also be involved in equipment rebuilds. The objective is to get the machine operator to accept ownership for machine maintenance, to understand the relationship between operation and wear and tear, to contribute suggestions for improvement of equipment reliability, and to be skilled maintenance resource with strong knowledge of machine function available at the first sign of operational problems.

TPM emphasises the need to diagnose root cause of maintenance problems. Permanent fixes are sought; Band-Aid repairs are unacceptable. Suggestions are aggressively sought on how to modify machine design to improve its reliability, serviceability, or state monitoring and these modifications are implemented quickly. Checks performed by maintenance technicians are very extensive in nature and incorporate predictive maintenance practices. There is also extensive use of visual controls. Parts and hoses are clearly labeled, schematic diagrams are posted, and important status gauges are easy to read. Maintenance records, including appropriate graphical displays, are located on the machine itself, and not kept in a remote file. These displays should include charts that document and that PM procedures were performed according to schedule. Preventive maintenance is given higher priority than production; a PM procedure must not be skipped for the sake of production. A key performance measure is the availability of the machine during scheduled operational time. Note that equipment utilisation is forbidden as a performance measure.

Potential for Mining Application: PM is widely accepted in the mining industry today and has led to substantial performance improvements. We believe that TPM would result in further improvement and could be readily adopted by the industry. A key benefit is faster learning about the weaknesses of equipment and resolution of these weaknesses through permanent design fixes. We note that such learning has resulted in remarkably more reliable production equipment in the coal industry over the last 20 years. TPM is a means for systematically making these discoveries and should result in a much faster rate of discovery than occurs in its absence. It would be particularly valuable to institute on a process that utilises new equipment and/or procedures.

5.1.5. *Flexibility*

Flexible production systems can (i) switch between different products in the product mix with minimal cost and loss of available operating time (product change flexibility), and (ii) vary throughput rate to match demand *with a proportionate change in input resource requirements*, especially manpower (capacity flexibility).

In lean production, flexibility is attained through the use of flexible equipment, setup reduction techniques, and a flexible workforce.

Lean production systems prefer the use of low cost, low capacity, and multi-purpose production equipment to expensive, high capacity, specialised equipment. The former is easily replicated and used in lines or cells dedicated to *product families* (subsets of the total product mix). The latter would only be preferred in high volume operations with little or no product differentiation.

The leveling objective of flow systems is only practical in production systems where setup times are small, otherwise the frequent switching between products results in excessive loss of production capacity. The principles espoused under the setup analysis procedure called *Single Minute Change of Die (SMED)* have proven effective in case after case to reduce setup times tremendously, by factors of 10–100 or more.¹⁰ These include ideas such as the conduct of external preparatory operations while equipment continues operation, parallel execution of setup tasks, connector designs that enable quick dismantling of equipment, and various methods to eliminate the need for equipment adjustment during product changeover. (The use of the term “die” in the SMED acronym follows from their practical application to stamping dies where these principles were first developed. They are, however, quite general concepts.) Setup reduction is one of the first steps companies undertake as they begin to implement lean production approaches.

Lean production systems seek a flexible workforce where each individual can man numerous operations and genuine teamwork is practiced (*shojinka*). This, of course, requires extensive cross training, but the investment is considered worthwhile. The resulting flexibility of work assignment enables implementation of the principle “*separate man from machine.*” Here, one individual works multiple machines each production cycle in contrast to traditional practice to assign one individual per machine. The underlying motivation is that in most traditional manufacturing environments, labor is the most significant cost component. High utilisation of man in value-added activity is far more important than high utilisation of equipment. Flexibility in work assignment is the principal means for capacity adjustment in lean production systems; and it allows full utilisation of man and minimal manning of the production process as current production requirements dictate. (In slack demand periods, excess workers are re-deployed to continuous improvement activity, which is value-added; they are never left with significant idle time.) Additional benefits of a flexible workforce include (i) faster organisational learning, since each task is viewed from multiple perspectives; (ii) employees gain a global perspective of the production process, which facilitates teamwork as well as their ability to identify process improvements; and (iii) a ability to rotate jobs (e.g. every two hours), which reduces fatigue, increases alertness, and offers various ergonomics advantages, including reduction of repetitive motion injuries.

Potential for Mining Application: In contrast to manufacturing operations, mining operations tend to be cyclic, with most setups occurring between successive

cycles. A wise strategy often is to devise systems that increase the cycle duration and thereby minimise the frequency that setups are needed. The use of deep-cut continuous miner systems is an example of such an approach. Careful mine layout can also be useful in this regard (e.g. obtaining longer panel lengths).

It remains, nonetheless, highly desirable to reduce the duration of these setups when they are required. The longwall panel move is an example where many of the SMED principles mentioned above have already been implemented with great success. Panel moves today take only a fraction of time that they did 25 years ago. Place changes in room and pillar mining might benefit substantially from application of SMED principles. The supersection concept, where a redundant continuous miner is used and set up in a new cut while the other miner continues operating, might be a reasonable strategy. However, because this is a high cost machine, lean practitioners would be reluctant to take this approach until after an aggressive attempt to implement SMED principles. General experience suggests that dramatic reductions are generally possible.

The feasibility of quick change between products in mining can be problematic, and the requirements for effecting such changes have little in common with manufacturing product changeover. Product change often involves extracting a different part of the reserve base. High volume mining systems (e.g. draglines) and underground systems in general tend to be immobile, making frequent machine site changes impractical. Low volume surface mining systems tend to be more flexible in this regard. In a multi-product operation, a lean mine would tend to favor lower volume, more flexible extraction systems. In certain situations the increased value of the reserves obtained through making a range of carefully targeted products might offset increased costs of production through use of low volume extraction systems which have lower economies of scale. Underground mining would require materials handling systems that permit segregation of material by source. This is difficult to accomplish using conveyor networks, although automated material tracking and splitting probably could, with some development effort, overcome this limitation. Extraction sequence planning is critical. The objective would be to concurrently maintain faces with varying characteristics as required by the product mix or to maintain faces at the extremes of the range of characteristics so that compositional targets can be attained by blending. With effort, this is possible and, indeed, has been successfully implemented at a number of mining operations.

The use of cross training and teamwork is clearly desirable in mining and some mines have capabilities along this line. Lean philosophy and practice, however, clarifies the ends to which the flexibility might be applied. One key application is to obtain the minimal manning of a process. Idle operator time is a waste and lean systems seek to re-deploy unneeded personnel to other production activity or in continuous improvement efforts. Second, is the related practice of adjusting capacity of a process to match demand while still attaining 100% utilisation of man. For example, if the product mix requires 500 tons of coal from a particular mining section, a lean system might man this section with a smaller number people working

in cross-trained teams in order to attain this target quantity with minimal labor input and waste.

5.2. Design for flow

Design for flow first requires a partitioning of the company's product mix and machine resources into subsets. This entails definition of *product families* and *machine groups* dedicated to the production of the particular members of that family. The idea is to co-produce products with similar routings on common process lines. (Note that the common alternative used in traditional manufacturing is to route a product through a functionally laid out plant using batch-and-queue manufacturing.) These lines can be laid out so that intra-station transportation can be minimised and the similar processing requirements among the members of the product family reduce setup requirements when product switches are made. There must be balance between production capacity of the machine group and demand for the product family. Great care is taken in system design to attain both static and dynamic capacity balance between operations in a machine group for each member of the product family. Such balance reduces the need for material buffers in the transfer line to maintain throughput and simplifies production control. The ideal is synchronous operation of each station, where each completes its operational cycle on a predefined *takt time* pacing the production system (the specification of takt time is discussed below), although balance between workstations over longer intervals is often a practical necessity. Note that machinery would generally have excess production capacity, and the goal in balancing would be to attain 100% labor utilisation, not 100% machine utilisation. (High capital and depreciation costs for mining equipment would tend to make machine utilisation more important in certain cases.) The system is switched frequently between products to meet the leveling objective, requiring rapid changeover capability. Since continuous flow requires serial transfer of product between stations with minimal material buffers, processes meeting the stability requirements noted above are essential. With non-stable processes, throughput capacity would suffer tremendously.

Potential for mining application: Attainment of flow, as defined above, would undoubtedly benefit mining systems as much as it benefits manufacturing systems. However, design for flow in mining would need to take different strategies, as the sophisticated analytical techniques and flow design tools of manufacturing have little direct relevance to mining applications. Unfortunately, there are no firmly established methods for accomplishing this sort of process design in mining.

To illustrate the potential advantages of flow, consider fractionated plants used in the crushed stone industry. Fractionated plants are employed at high volume quarries that make a wide product mix. To obtain flexibility in the product mix, the stone is crushed and screened into size intervals. Each size interval is, in turn, placed in a separate stockpile. When an order comes in, stone is selected from the appropriate piles and blended to make the desired size composition. Although

flexible, fractionated plants are certainly not lean. The capital cost for the material handling system is high and all of the extensive handling operations are non-value-added. Flexibility is achieved in this system through inventory, not through flexible, controlled operations, as desired in lean production systems. A lean system designed to provide the same product variety would employ far fewer stockpiles (or bins) and much less inventory. (Accordingly, capital costs would be much lower and the concept could be applied at much smaller scale.) The assignment of size classifications to this reduced storage space would be dynamic, responding to the temporal pattern of customer demand. The lean crushing plant would be designed for rapid changeover between products as would the mine's extraction and materials handling system. Extraction activity would be closely linked to short term demand for various products. Great attention would be given to specify crusher and screen settings that minimise rejects, specifically undersize material that is difficult to market.

6. Pull/Just-in-time

Just-in-time is a production control system for producing the precise quantity of product needed at the time that it is needed. Ostensibly, the objective of just-in-time is the balance and synchronisation of the quantity of production with demand, thereby eliminating the wastes of overproduction. However, this is not completely true. External demand for products is often highly variable over time with strong random components. Most practical production systems employing the flow principle cannot be directly interfaced to such highly variable demand. Instead, under such circumstances, this demand must be smoothed, averaging actual orders and forecast demand over future time intervals of appropriate duration. The interval must not be so long as to obscure real shifts and trends in demand to which we want our system to respond. On the other hand, it must not be so short that the averaging process does not filter random oscillations. The smoothed demand figure defines a *takt time* used to pace the production system. Takt time is the allotted production time to produce 1 unit of product and is obtained simply by dividing the duration of the scheduled production interval by the demand quantity that the production system should supply during that interval. Takt time provides the basis for static capacity balance of the flow system.

Traditional production control, including that utilised at mines is *push*. In such a system, work is scheduled by initiating the job at the beginning of the production sequence. The job orders respond to committed or anticipated delivery dates, and the timing calculation involves an estimate of production lead times. Once production is initiated, the product is pushed through the remainder of its routing and no further control or intervention is planned.

In contrast, just-in-time systems employ *pull* production control. Pull differs from push in that jobs are authorised, not scheduled. The pull system, in its most common form, works as follows (Fig. 2). For a given product, upon the termination

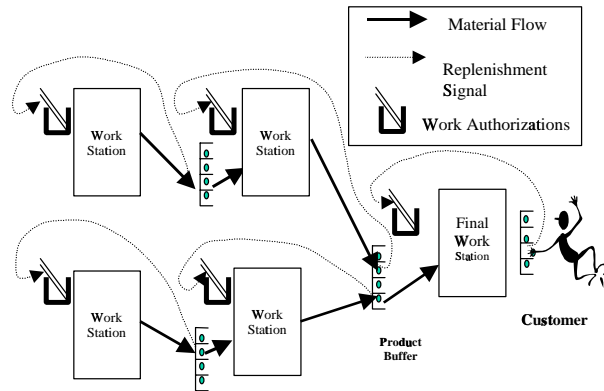


Fig. 2. Pull production control.

of each takt interval a unit of the finished good is *pulled* from the output buffer of the last workstation in the flow line. This creates an *authorisation* for that workstation to produce another unit of that product. (The authorisation is often communicated in the form of a *kanban* card.) The authorisation enters a first-come-first-served queue of authorisations at the workstation. This workstation (and all others in the system) produces only when it has an authorisation, a discipline that is strictly followed even if the station goes idle. As service of a particular production authorisation begins, product is consumed from the workstation's input buffers. This consumption, in turn, triggers release of an authorisation, which is sent to the appropriate upstream workstation in order to replenish the material consumed. This authorisation enters the queue at the upstream station and the process is repeated. In this manner, work authorisations chain backward through the production system in the reverse direction of material flow, *limiting the quantity produced to the quantity actually demanded*. An additional feature of pull systems is that the number of authorisations that circulate between each pair of successive workstations on a product routing is fixed at a pre-defined level, thereby capping the in-process inventory. If the inventory cap is small, total production lead times are small.

We make three additional notes to clarify how pull systems are implemented in practice. First, the definition of a "workstation" in a pull system differs from case to case. A group of sequential operations in a continuous flow system would typically be treated as a single workstation in a pull system and a (simpler) secondary production control system would be utilised between the operations within the workstation. Second, variants of this system are available for operations that, because of extensive setup requirements or process operating characteristics, must produce in large batches. Called signal kanban systems, the production authorisation signal is sent when inventory of a particular product drops below a particular level. When this authorisation is serviced, a fixed quantity of that product is produced to replenish the stock in its output buffer. Finally, we note that the pull system should trans-

late across inter-organisational boundaries. This enables the match of production with demand, low inventories, and low production lead times to exist throughout the entire extended enterprise. In the absence of such chaining of the pull system throughout the supply chain, the result tends to be a shift of inventory from the parent company to the supplier, an undesirable and unnecessary consequence.

Note that pull systems respond automatically to process upsets. If a downstream operation fails, authorisations to the upstream station stop, and production operations at that station become *blocked*, preventing excess inventory accumulation and overproduction. If the station is down long enough, the downstream station will eventually be *starved* for input material and its production will also stop. Intra-station inventory caps may be specified so that incidence of starving or blocking is rare, especially for capacity-limiting (bottleneck) operations. Pull systems control both the total quantity and the distribution of inventory in the production system. Push systems offer no such control over inventory levels and do not respond to process upsets. In the absence of such control, a push system with low inventory will result in frequent starvation and loss of throughput capacity. To prevent this, management generally floods the system with inventory. This, in turn, leads directly to long and highly variable production lead times. The product is seldom produced according to the desired schedule and the long lead-time forces build-to-forecast. Forecasts themselves are often in error and this further exacerbates coordination of production with demand. Overall, push systems are much less controllable than pull systems.¹¹

There is a very important relationship between pull and flow. If the number of circulating work authorisations and, hence, inventory, is kept high, pull can be implemented on systems with poor flow. It is practice in lean production to start with relatively high inventory levels in the pull system and then systematically reduce these levels over time. This creates intentional stress on the production system, motivating efforts to improve flow. Problems, such as low equipment reliability, supply delivery problems, quality problems at a particular workstation, etc. become visible as the inventory is reduced to lower levels. Once visible, the perfection mechanism is employed to eliminate the problems permanently. Hence, pull is utilised to motivate improvements in flow. Moreover, as noted in the previous section, once high levels of flow are realised, production control becomes simpler, and pull is less important.

6.1. *Potential for mining application*

An important initial comment on pull is that the objective is to closely balance and synchronise production with demand. It is *never* an objective, as common at many mining operations, to maximise production output from the system. Moreover, efforts by personnel to set production records in a lean mine would be forbidden. Instead, the goal in lean production is to establish stable production processes that can be relied upon to produce the required quantity at the time requested

to do so. Moreover, this production would be achieved with minimal waste of resources. Production in excess of the quantity demanded always results in losses; and, in mining, the most significant of these is likely to be discounting to move the inventory.

Concerning application of just in time at mines, the implementation of pull production control for supplies and materials would be straightforward. Kanban systems could be used to coordinate the flow of supplies simply and automatically throughout the mine, reducing inventory levels while insuring adequate supplies are available when and where needed. Such a system should be easier to manage than existing supply systems at most mines because of the simple information flow.

Broader applications of pull seem reasonable. For example, in the utility industry, one could visualise a pull system that extended from the boiler to the mine face. Time would be partitioned into intervals over which electricity demand is expected to be reasonably stable (say a 2-week interval). Expected coal demand would be communicated to the mine for that interval and over a future planning horizon of intermediate duration (say 6 months) so that overall capacity planning could be undertaken. A production authorisation might be issued for each coal unit consumed (e.g. 1000 tons) and these authorisations transmitted back to the mine on regular intervals. The mine would thereby be expected to respond to actual coal consumption at the utility. However, note that deviation of actual and planned consumption would be limited to plus or minus 10% (a general rule of thumb for just-in-time systems). Transportation would be carefully coordinated so that trains, barges, or other haulage units arrived on at the mine on a highly uniform schedule over time in order to keep demand from the utility as level as possible (*heijunka*). The production authorisations would translate through the inventory at the mine back to the working faces, and these faces would work only upon authorisation. Because of stability built into the production system, the face could be expected to reliably respond to the authorisation in timely manner. Inventory levels throughout the system would be low, although safety stocks would be kept on hand at both the mine and utility in the event of unexpected disruptions. Special care might be taken to deal with major seasonalities in demand (e.g. a coal mine might seek a southern customer in the summer with high cooling loads to compensate for drops in consumption at the northern utility where they sell most of their product) in order to level demand as much as practical over the year.

We note that multi-product-mining operations tend to share one aspect in common with certain manufacturing operations: a very high variety of products that share a common process routing. In such a situation, implementation of the pull system as described above is difficult because it requires that buffers be established for each type of product between each stage in the production process. When the number of products is large, this is impractical. CONWIP¹¹ is an alternative implementation of the pull system that overcomes this limitation. Like other pull systems, it caps total inventory levels in the system. When a unit of product is pulled at the final station, a production authorisation proceeds to the beginning

of the production process to replace it. The type of product authorised at the beginning station may differ from the one just produced. Different product types need not be segregated into separate buffers as they flow down the line and simple systems can be implemented to control processing priorities at a station. CONWIP systems retain most, but not all, of the advantages of other pull production systems while enabling pull to be implemented in high variety situations. It appears that such a production control strategy might be useful in multi-product systems such as the lean fractionated plant described above.

7. Perfection

The three major elements of the lean philosophy that we have established so far have focused on (i) the need to assess both product design and all activities in its production from the perspective whether that feature or process adds value in the eyes of the customer, and (ii) ideals for structuring and operating the production system such as continuous flow, zero inventory, just-in-time production, zero defects, and 100% reliability. In the lean philosophy, the final major element, *perfection*, is the systematic quest to attain both these production ideals and maximum value for the customer through continuous improvement, or kaizen, efforts. The goal is to seek perfection in all of these measures through continuous pursuit of incremental gains in product design and the design/operation of the production system. Although perfection has much in common with the general concept of continuous quality improvement, there are some important differences, and we will point these out.

Benchmarking of performance measures with other companies is common practice in industry today, but its role is limited in lean production. In the lean philosophy, perfection is considered the genuine benchmark. This is not considered romantic idealism or wishful thinking. To seek perfection, it must be defined and quantified. The ideals for production system design and operation mentioned earlier provide part of this definition (zero inventory, zero defects, continuous flow, level production over small time interval, etc.). But precise definitions of perfection are sought in other areas of lean production. For example, in the practice of target costing, both *perfect-* and *unavoidable-waste-free target costs* are quantified. The former is the cost of production if all identifiable wastes are eliminated from the production process (e.g. transportation, inventory holding costs, inspection, etc.). The latter allows certain wastes that cannot be avoided without major redesign of the product or production process to form part of the target cost. The latter is a near-term product cost target that the company seeks to achieve. The former is a long-term goal. The quest for perfection involves determining information like this to set demanding, but achievable, improvement goals. Benchmark information is sometimes useful in near-term goal setting. However, the dangers of “resting on your laurels” once performance reaches benchmark levels is recognised and avoided.

Standardised work plays a key role in the quest for perfection. First, it provides a quantified baseline upon which any proposal for improvement can be judged; as

the saying goes, “without standards there can be no improvement.” Second, standardised work controls variance and this creates an environment where the effects of change in practice are easily measured during shop-floor experiments. The effects of the change will be apparent, not obfuscated by the random effects of uncontrolled factors. Even changes that offer small incremental performance gains can be quickly recognised as beneficial and implemented in the new standard. Moreover, when problems with the operation occur, the first thing to check is whether the source of the problems is failure to follow standardised work. If this is not true, it is clear that the standard procedure is in need of refinement.

In lean production, the quest for perfection involves the intellectual contributions of everyone from the lowest to the highest levels in the organisation. It is expected that personnel will work hard to improve themselves out of a job. In fact, when kaizen efforts result in an ability to eliminate a position, it is a common practice to remove the *best* worker from the group. This is considered an honor for the re-deployed worker; moreover, it makes sense for the company as well since this worker is likely to be innovative in his/her new assignment.

As mentioned earlier, essentially permanent job security is a prerequisite for employees to pursue earnestly and aggressively the elimination of waste. Lean producers are very reluctant to hire employees in good times and lay off only in the case of last resort. Companies converting to lean with surplus employees might layoff employees to a sustainable level on day one, but not thereafter. Lean companies work to instill a sense of security and trust in the employee. Much of this trust comes from the employees believing that they are viewed as intellectual assets valued by management even more than physical and monetary assets. Employees have to be confident that they are not going to be discarded like excess baggage at the first sign the ship is taking on water. While no one can promise lifetime employment, or guarantee layoffs will never occur, lean management principles have the fundamental policy that layoffs are a last resort, not a first option. All other options are exhausted before layoffs are considered.

All workers are trained in problem solving, specifically the classical Plan-Do-Check-Act (PDCA) cycle. The goal is to always seek the root cause of problems and permanent fixes. Team members are instructed in the use of various tools such as Pareto diagrams (to prioritise problems), cause/effect diagrams and the 5-Whys strategy (for determining root cause), and brainstorming techniques (for devising problem countermeasures). All kaizen efforts are accomplished through teams in order to reap the benefits of collective brainpower, buy-in, and the positive social impact of teams on energy and morale. As noted above, the lean worker also has knowledge of basic industrial engineering principles and techniques, which provides a foundation for defining operational improvements. Suggestion systems are employed to seek individual ideas. These are not simply boxes on the wall that are emptied out once a month. For example, the average number of implemented suggestions per employee at TMMK in Georgetown, KY exceeds 60 per year (there are 7000 total employees) and in 1998 the estimated savings from that year's

suggestions were valued at in excess of \$70M. In order to have such effectiveness, the suggestion systems must offer significant rewards and decisions to implement must be made at a low level and quickly. Lean employees must be team players, not individualists and employee screening is done to insure this.

It is a practice in lean production to make problems visible; indeed, proactive measures are taken to make them visible. One basic strategy is the use of *visual control*. Workplaces are kept highly organised, all unnecessary materials are removed, and tidiness of equipment and work area is maintained continuously. In addition, through careful layout and the use of signs and visual displays, one seeks to make it easy for *anyone* to understand the production process and the current state of the system. In such an environment, abnormalities become immediately evident (e.g. a machine is leaking oil, or stocks of supplies and consumables are unacceptably low). As part of visual control, the work team defines measures that reflects the performance of their operations and posts the current status and trends visually to identify problems for all to see and to motivate improvements. Problems are not swept under the rug. Problems are opportunities for improvement, and blame is avoided.

A second strategy for making problems visible involves the relationship between pull production and flow, mentioned above. Inventory levels are intentionally and incrementally ratcheted down, with full expectation that operating problems will ensue. These problems, now clearly apparent, are viewed as opportunities for improvement and become a focus for kaizen efforts.

A final strategy for making problems visible is the authority given to all employees to stop the production process when problems occur, *jidoka*. This usually starts by setting off an audio or visual alarm (e.g. pulling the andon cord along a product line or in a work cell), which brings fellow team-members to assist. When the problem gets more serious, especially in the event of quality problems, the line is shut down. Statistics are kept on the number of times each station sounds an alarm. The information is used to identify important areas for continuous improvement.

The point of all of three of these strategies is to make problems visible, to identify the root cause of the problem and to make permanent fixes. This promotes rapid organisational learning and evolution of the production system to a higher and higher level of functioning. Band-aid solutions to problems are avoided.

7.1. *Potential for mining application*

Undoubtedly the principles for perfection could be equally as effective in a mining situation as they are in any other. It is important to recognise that these strategies depend on other aspects of lean production (e.g. visual control, standardised work, TPM, and the just-in-time/flow interrelationship) to obtain much of their effectiveness and power.

The implementation of continuous improvement would require changes in values and organisational culture at many mines. Management must esteem employees as

much for their minds as they are for their arms and legs. Clear buy-in from top management to the concept of kaizen, their willingness to surrender control to their employees, and strong mutual trust between management and labor is essential. Lean implementations have been successful at union organisations. Union workers receive high pay, security, and improved work environments. In return, they are expected to be flexible, highly trained, and make intellectual contributions. Training in problem solving, teamwork, TPM, and basic production analysis tools is required through all levels in the organisation.

The practice of perfection as we have described herein would, desirably, shift the emphasis of mine management's attention away from production (and misleading performance measures such as last shift's production output and last week's equipment utilisation) to a focus on process. If waste is removed from the process and the stability, flexibility, and flow of operations is improved, the desired performance objectives in terms of low production cost, timely delivery in conformance to demand, and high product quality will follow as a direct consequence.

8. Conclusion

Lean production appears to be highly applicable to mining as it is to many other production systems. Value definition and value stream analysis, standardised work, quality-at-the-source, total productive maintenance, flexible workforce, setup reduction techniques, and continuous improvement approaches could be implemented directly in the mining industry. Techniques design for flow do not transfer from manufacturing to mining, but the benefits from flow, nonetheless, should be highly valuable. Studies to compare alternative means to attain flow in mining operations would be valuable in clarifying this issue. Given the bulk nature of mining products, pull production control implementations will differ from those in manufacturing, but this approach should better coordinate production with demand than existing systems and should motivate other process improvements. To gain the full benefits of lean, it should not be implemented piecemeal. As the discussion above illustrated, value stream analysis, flow, pull, and perfection are highly interdependent. Implementation of lean is never easy. It takes considerable time, and it requires strong buy-in and leadership from top management, change agents, and high investments in training. (Numerous companies provide training services for employees at all levels.) However, the tremendous documented performance gains that have resulted in implementing lean has lead to many companies making this commitment and starting their lean journey.

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